EXPERIMENT 9

I-V CHARACTERISTICS OF A *p-n* JUNCTION DIODE

Structure

9.1 INTRODUCTION

From your school physics courses, you may recall that some materials like metals conduct electric current readily and have low resistivity. We call them conductors. Other materials like wood and plastic, called insulators, are poor conductors of electric current as these have high resistivity. There are materials that possess resistivity lower than insulators but higher than conductors and these are called **semiconductors**. So you know that materials are broadly classified into conductors, insulators and semiconductors depending on their resistivity. The resistivity of conductors is of the order of $10^{-7}\ \Omega\text{m}$ and that of insulators of the order of $10^{12} - 10^{24}\ \Omega\text{m}$. The resistivity of semiconductors lies in-between these values.

A *p-n* junction diode is a semiconductor device that forms the backbone of electronic and computer equipment. You may know that micro-electronic chips are the cores of computers and these are made up of semiconductor devices including *p-n* junction diodes. In this experiment you will draw the *I-V* characteristics of a *p-n* junction diode. This will help you learn how diodes work as rectifiers when you do the next experiment.

However, before doing Experiments 9 and 10, you should revise the basic concepts of semiconductors and the physics underlying a *p-n* junction diode. We have briefly explained these concepts in Secs. 9.2 and 9.3. Then in Sec. 9.4, we describe how to do this experiment. In this experiment, you will learn how to test whether a *p-n* junction diode is working or not.

You will also learn how to connect the circuit for taking current and voltage measurements for the diode in forward and reverse biased conditions. You will then draw the *I-V* characteristics for the diode and interpret them.

Expected Skills

After performing this experiment, you should be able to:

- connect the circuit for forward and reverse biased *p-n* junction diode taking due precautions;
- make the measurements of current and voltage in the circuit; and
- draw and interpret the current-voltage (*I-V*) characteristic curves for a *p-n* junction diode.

The apparatus required for this experiment is listed below.

Apparatus required

A general purpose *p-n* junction diode, a variable power supply with voltage 0-10 V, voltmeter (0-10 V), milliammeter (0-50 mA), resistance box (up to 10 kΩ), microammeter (0-50μA), multimeter, breadboard and connecting wires.

9.2 BASICS OF SEMICONDUCTORS

From your school physics, you should be familiar with the basic physics of semiconductors. You have studied about *p*-type and *n*-type semiconductors and the *p-n* junction diode. However, in this section, we revise the basic concepts related to this experiment so that you can perform the experiment with a better understanding.

As we stated in the introduction, semiconductors are materials that have resistivity values between the resistivity of conductors ($\sim 10^{-7}\,\Omega\text{m}$) and insulators ($\sim 10^{12} - 10^{24}\,\Omega\text{m}$). Semiconductors are of two types: **intrinsic** and **extrinsic**. A pure semiconductor is said to be intrinsic semiconductor. Examples of the most commonly used intrinsic semiconductors are crystalline silicon and germanium.

In recent years, many more intrinsic semiconductors such as compound semiconductors, amorphous semiconductors and semiconducting polymers have been developed. However, in this experiment, we shall use only diodes made of silicon (or germanium). The resistivity of intrinsic semiconductors is high and therefore, they are of little use in electronics.

Doping is a process of adding small quantities of another element, called impurity, in a pure/intrinsic semiconductor in order to increase its conductivity.

However, the conductivity of semiconductors can be increased (or their resistivity decreased) if impurities of appropriate elements are added to them in small quantities. This process is called **doping**. Such doped semiconductors are termed **extrinsic** semiconductors. It is found that if silicon or germanium is doped with a suitable pentavalent atom like phosphorus, antimony or arsenic, their resistivity decreases and conductivity increases by many orders. Thus, these become suitable for many uses in electronic circuits. Let us briefly explain how this is made possible.

Silicon (Si) (atomic number 14) has four valence electrons. The bonding structure of intrinsic silicon is shown in Fig. 9.1. Note from the figure that each silicon atom is sharing one valence electron each with four neighbouring atoms. This kind of sharing of electrons is called **covalent bonding**. This is what provides stability to silicon atoms in a crystal. This is true for germanium as well.

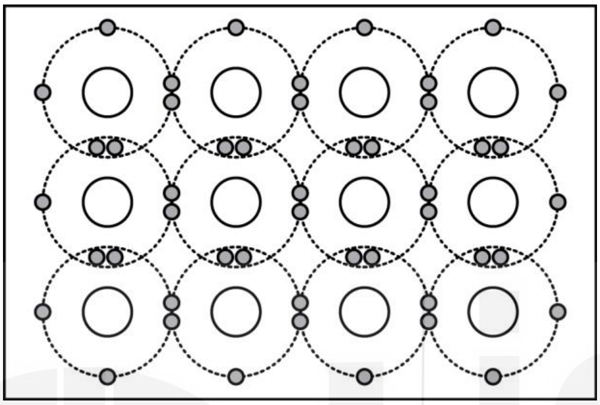

Fig. 9.1: **Covalent bonding in an intrinsic silicon semiconductor.**

Germanium (Ge) (atomic number 32) too has four valence electrons. So, its structure is the same as that of silicon. Four valence electrons in each atom of Ge are shared by four neighbouring atoms as shown for silicon in Fig. 9.1.

When silicon (or germanium) is doped with a pentavalent impurity (that has five valence electrons), four valence electrons of the impurity form a covalent bond with four neighbouring silicon or germanium atoms. The fifth valence electron is not a part of the bond and is free to move in the crystal (see Fig. 9.2). Thus, when a pentavalent impurity is added to a silicon or germanium crystal, it develops excess free electrons and is said to be an ***n*-type semiconductor**. Such an impurity which results in excess free electrons in an intrinsic semiconductor is known as a **donor impurity**.

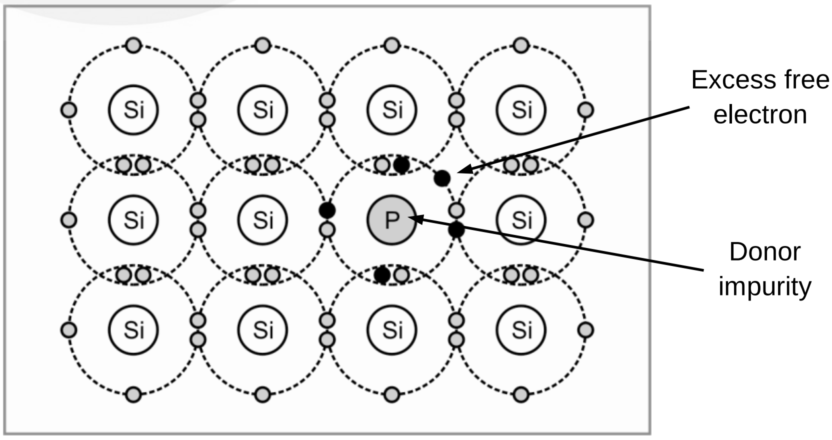

Fig. 9.2: **Structure of an *n*-type semiconductor doped with phosphorus.**

When silicon (or germanium) is doped with a trivalent impurity (that has three valence electrons) such as boron, aluminium, gallium or indium, three electrons of the impurity atoms form covalent bonds with three neighbouring silicon (or germanium) atoms. Thus, one deficiency (of an electron) is created per impurity atom doped in the silicon (or germanium) crystal (see Fig. 9.3). This deficiency (of an electron) is termed a **hole**.

So, when a trivalent impurity is added to a silicon or germanium crystal, it develops deficiencies of electrons (called holes) and is said to be a ***p*-type semiconductor**. Such an impurity is known as an **acceptor impurity**.

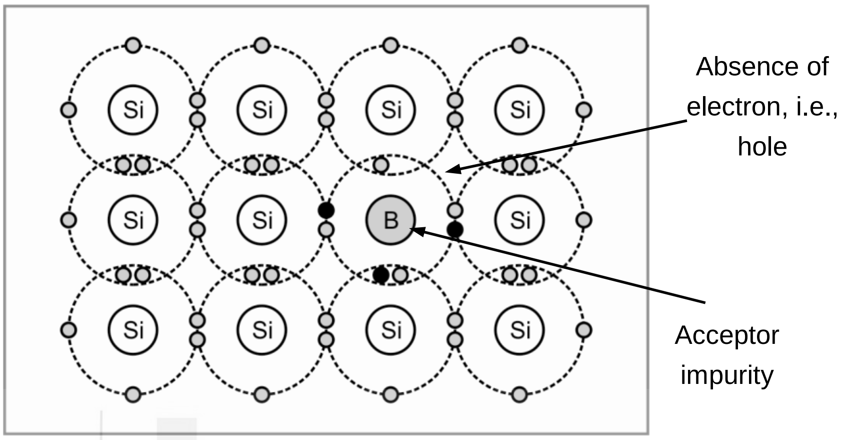

Fig. 9.3: **Structure of a** *p*-**type semiconductor doped with boron atom.**

With this brief revision of the very basic concepts of intrinsic semiconductors and extrinsic *n*-type and *p*-type semiconductors, you can learn the basic physics of a *p-n* junction diode. As you know, it is one of the most useful semiconductor devices.

Let us now learn about a *p-n* junction diode.

9.3 INTRODUCTION TO A *p-n* JUNCTION DIODE

A *p-n* junction is formed when donor impurities are introduced into one side and acceptor impurities into the other side of a single intrinsic semiconducting crystal (Fig. 9.4a). The boundary or interface between the *n*-type and *p*-type parts of the crystal is called the *p-n* junction. A *p-n* junction diode is a two terminal device formed by this kind of doping (Fig. 9.4b).

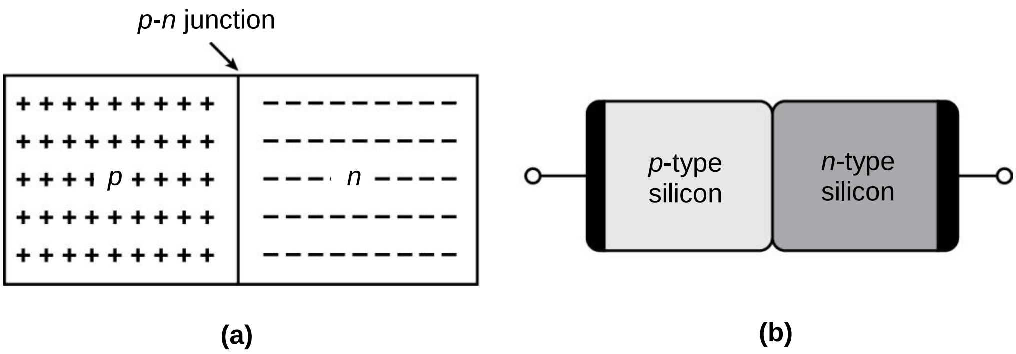

Fig. 9.4: **a) A** *p-n* **junction is the interface formed when a single crystal is doped with acceptor impurities on one side and donor impurities on the other so that holes are the majority charge carriers on the** *p*-**side and electrons on the** *n*-**side; b)** *p-n* **junction diode.**

We now explain how charge carriers behave in the *p-n* junction.

9.3.1 Working of a *p-n* Junction

Note that the *n*-region of the semiconducting crystal has a greater concentration of electrons and its *p*-region has a greater concentration of holes. In such a situation, electrons and holes tend to *diffuse* from regions of higher concentration to regions with lower concentrations of electrons and holes. So, electrons *diffuse* from the *n*-region to the *p*-region and holes *diffuse* from the *p*-region to the *n*-region (see Fig. 9.5a).

You may think that this process should continue till such time as the number of electrons or holes in both regions becomes equal. But this is not so. When electrons diffuse from the *n*-region to the *p*-region, positively charged donor ions are left behind near the *p-n* junction.

Similarly, the diffusion of holes from the *p*-region to the *n*-region leaves behind negatively charged acceptor ions near the junction. Thus, the diffusion of electrons and holes leads to the accumulation of positive and negative ions near the junction (Fig. 9.5b).

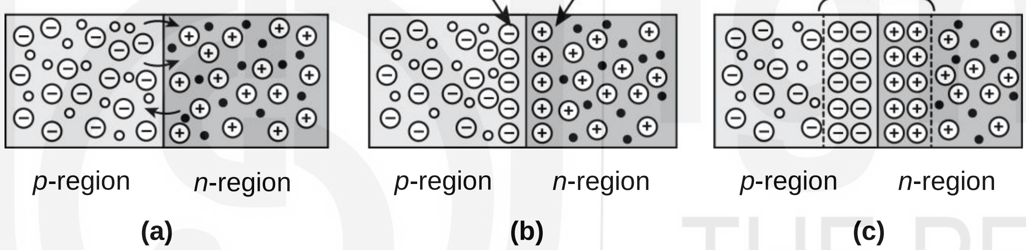

Fig. 9.5: **a) Diffusion of electrons and holes across the *p-n* junction; b) accumulation of negative acceptor ions and positive donor ions near the *p-n* junction; c) depletion region.**

Due to accumulation of charges near the junction, an electric field is established. This gives rise to electrostatic potential, known as **barrier potential**. It is called the **barrier potential** because it prevents further movement of charge carriers across the *p-n* junction when there is no external electric field.

As a result, a narrow region near the junction is depleted of mobile charge carriers. It is about 0.5 μm thick and is called the **depletion region** or **space-charge region** as no mobile *charge carriers* are present in it (Fig. 9.5c). Thus, depletion region acts like a barrier that opposes the flow of electrons from *n-region* and holes from *p-region*.

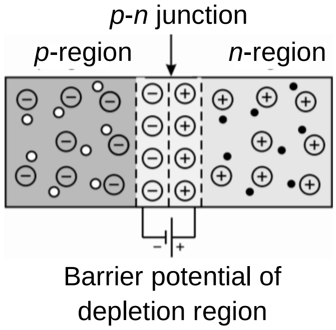

Fig. 9.6: **Barrier potential due to depletion region.**

This barrier potential has polarities, as shown in Fig. 9.6. The barrier potential is a characteristic of the semiconductor material. It is about 0.3 eV for germanium and 0.7 eV for silicon. How can we overcome the barrier potential so that current can flow across the junction? In the next section, you will learn how the *p-n* junction diode can be biased by applying external voltage so that it allows current to flow through it. This is called the forward bias. You will also learn what happens when it is in reverse bias.

9.3.2 Forward and Reverse Biased *p-n* Junction Diode

Let us see what happens when we bias the *p-n* junction diode. We can bias a *p-n* junction diode by applying an external electric field via a battery as shown in Fig. 9.7a. Note that the *p*-end of the diode is connected to the positive terminal of the battery and its *n*-end to the negative terminal. The diode is then said to be **forward biased**.

When the external voltage exceeds the barrier potential, it becomes easier for the electrons to cross the *p-n* junction and move from the *n*-region to the *p*-region and the holes to cross over from the *p*-region to the *n*-region. This gives rise to a current in the diode from the *p*-region to the *n*-region. This current is called the **forward current**. When we increase the forward bias voltage across the junction, the forward current increases and is typically of the order of a few milliamperes. So, in forward bias, the *p-n* junction diode offers low resistance to the flow of current. The value of the junction resistance, called the forward resistance, is in the range 10 Ω to 30 Ω.

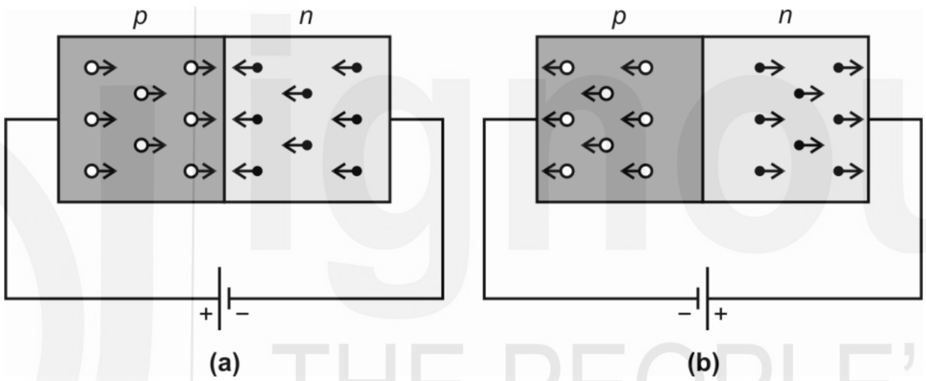

Fig. 9.7: **a) Forward biased; b) reverse biased *p-n* junction diode.**

When the terminals of the battery are reversed, that is, we connect the *p*-end to the negative terminal of the battery and the *n*-end to its positive terminal as in Fig. 9.7b, the *p-n* junction diode is said to be **reverse biased**. In this case, the electrons in the *n*-region and the holes in the *p*-region move away from the junction, which means that no current should flow across the junction. But is it really so? Does no current flow at all when the junction is reverse biased?

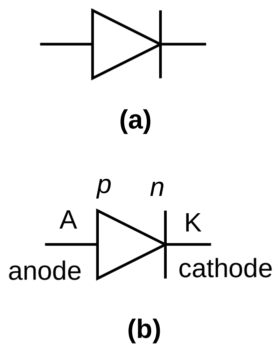

Fig. 9.8: **a) Symbol of a *p-n* junction diode; b) anode and cathode in a *p-n* junction diode.**

Actually, a small current does flow across the junction because a few electron-hole pairs are generated due to thermal excitations; these are called **minority charge carriers**. The current due to minority charge carriers is called the **reverse saturation current** or **leakage current**. It is of the order of a few nanoamperes to microamperes. In most commercially available diodes, the reverse current is almost constant and independent of the applied voltage.

So, in reverse bias, the *p-n* junction diode offers high resistance to the flow of current in the range 10 kΩ to 100 kΩ. The resistance of a *p-n* junction diode can be tested with the help of a multimeter. By measuring diode resistance by a multimeter, we can also find out if the diode is working properly. The symbol of the *p-n* junction diode is shown in Fig. 9.8a. The arrow represents the direction of current flow when the diode is forward biased. See Fig. 9.8b. The letter A in it corresponds to the *p*-region, which acts as an anode in the diode. The letter K indicates the *n*-region, which corresponds to cathode in the diode.

You have just learnt that doping one side of a crystal with a donor impurity and the other side with an acceptor impurity yields a device called the *p-n* junction diode. This device offers low resistance when forward biased and high resistance when reverse biased. This property of the diode is used for rectifying ac as you will learn in the next experiment.

Fig. 9.9: **Marking on a *p-n* junction diode to identify anode and cathode.**

You should also be able to identify which end of the diode is the *p*-end and which one, its *n*-end. This will enable you to bias the diode correctly and take measurements. We can identify the anode and cathode of a diode directly by looking at it. To help in visual identification of anode and cathode, diode manufacturers usually print a small ring at one end of the body of the diode that corresponds to the cathode. This kind of a typical marking is shown in Fig. 9.9. **You must always refer to the manufacturer's catalogue to know the exact specifications of a diode and must operate the diode within its maximum current and peak inverse voltage ratings to prevent damaging it. Take help from your Counsellor to know these ratings.** With these basic ideas about semiconductors and the *p-n* junction diode, you can perform the experiment and draw the *I-V* characteristic curve for the diode.

9.4 *I-V* CHARACTERISTICS OF A *p-n* JUNCTION DIODE

In the first part of this experiment, you will learn how to test a *p-n* junction diode using a multimeter to determine if it is working properly. Then you will make the circuit connections as per the procedure described in Sec. 9.4.2. Finally, you will make current voltage measurements and draw the *I-V* characteristics of a *p-n* junction diode.

9.4.1 Testing a *p-n* Junction Diode

In this part of the experiment, you will use a multimeter to check if the *p-n* junction diode is working properly. You have learnt how to measure resistances using a multimeter (analogue or digital) in Experiment 1 of this course. You will use that skill to check the *p-n* junction diode. You have learnt in Sec. 9.3.2 that a *p-n* junction diode has low resistance when it is forward biased and high resistance when it is reverse biased. We can use this property to test the diode and also find out which of its ends is *p*-type and which one *n*-type. Here we give the steps for testing a *p-n* junction diode using a multimeter.

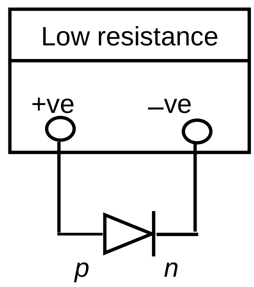

Fig. 9.10: **Testing of a *p-n* junction diode in forward bias.**

Testing a Diode with Multimeter
1. Set the function/range selector switch of the multimeter to the resistance measurement position in the range of 10 kΩ. This range is chosen so that the current through the diode is low (see Fig. 9.10).
2. Make zero adjustment if you are using an analog multimeter.
3. Identify the polarities of VΩ and COM terminals by using external voltmeter.

Insert the red lead of the multimeter in the terminal VΩ with positive polarity and its black lead in the negative polarity terminal COM.

If there are markings for *p*-type and *n*-type on the *p-n* junction diode then proceed as follows:

4. Connect the red lead to the *p*-side and black lead to the *n*-side. If the diode is in working condition, you should get a low resistance (~ 10 Ω to 10^2 Ω) reading (Fig.9.10). If the meter indicates a low resistance value, it means that the diode is working properly.

5. Now, put the selector in the high resistance position. Reverse the connection, i.e., connect black lead to *p*-end and red lead to *n*-end. You should get a very high resistance reading (Fig.9.11). If the meter indicates OL or a very high resistance, it means that the diode is working properly.

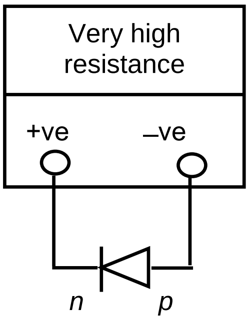

Fig. 9.11: **Testing of a** *p-n* **junction diode in reverse bias.**

If the multimeter shows zero or low resistance reading for forward as well as reverse connection, then the diode is damaged – it is short circuited.

If the diode shows a high resistance under both forward and reverse connections, then also it is damaged – it is open.

In both these cases, the diode is damaged and unusable.

Now suppose the **diode is unmarked** and you have to identify its *p*- and *n*-ends. You can easily do that by performing the procedure described above. **The end of the diode that shows low resistance when connected to the negative lead of the multimeter is its *n*-end and naturally, the other end is *p*-end.**

Now that you have followed the above steps and checked that you have a diode that is working properly, you are ready to make the circuit connections. But before that, you may like to answer an SAQ to check whether you have understood this section.

SAQ 1 – **Testing a** *p-n* **junction diode**

Suppose you are given an unmarked resistor and an unmarked *p-n* junction diode. How will you identify these?

9.4.2 Making Circuit Connections and Taking Observations

We now explain how to make the circuit connections and take observations for this experiment. **Before making the connections, do note down the ratings of the diode. Consult your Academic Counsellor to get those ratings for the diode that you are using. Make sure that you do not exceed them at any point while doing the experiment.**

Before making the circuit connections, check that the junction is working properly using a multimeter.

I. **Forward biasing the *p-n* junction diode**

Follow the steps given below to connect the circuit shown in Fig. 9.12:

1. Keep the power supply off and connect the positive terminal of the power supply to a resistance of about 500 kΩ. Connect the other end of the resistance to the positive terminal of the milliammeter.

2. Connect the negative terminal of the milliammeter to the anode of the diode and to the positive terminal of the voltmeter.

3. Connect the negative terminal of the power supply to the negative terminal of the voltmeter and the cathode.

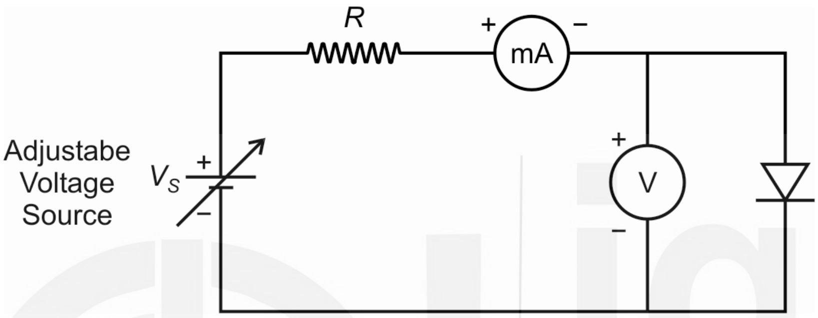

Fig. 9.12: **Circuit diagram for the *I-V* characteristics of a *p-n* junction in forward bias.**

4. Check the circuit connections.

5. Turn the voltage control knob of the power supply to its minimum position and then switch it on.

6. Increase the voltage in steps of 0.1 V and note corresponding values of current, until an appreciable deflection (of about 0.6 mA) is observed.

7. What do you observe when you increase the voltage? You will note that the current in the circuit is small as long as the applied voltage is smaller than the barrier potential. Once the applied voltage is more than the barrier potential, the current will increase rapidly with a small increase in the applied voltage. The forward voltage required to get the junction to conduct current is called the **knee voltage**. Beyond the knee voltage, the current in the circuit increases rapidly.

8. **Note that in no case should you increase the applied voltage beyond a certain limit. This is because the current in the circuit should not exceed the maximum forward current rating of the diode in the forward bias condition. Otherwise the diode can get damaged.**

9. Record your readings in Observation Table 9.1.

10. Next decrease the applied voltage in the same steps and note down the corresponding current values. Record these values also in Observation Table 9.1. Are the values of current same in both cases?

11. Calculate the mean value of current for each value of V and record it in the Table.

Observation Table 9.1: Current-voltage measurements for a forward-biased *p-n* junction diode

S.No.	Forward Voltage (V)	Forward Current (mA)		Mean Forward Current (mA)
		Increasing voltage	Decreasing voltage	
1.	0.0			
2.	0.1			
3.	0.2			
4.	0.3			
.	.			

In order to draw the *I-V* characteristics of the diode, you need to measure the currents corresponding to applied voltages when the diode is reverse biased. We now explain how to connect the circuit and make those measurements.

II. **Reverse biasing the *p-n* junction diode**

The circuit connections for reverse biasing the diode are shown in Fig. 9.13. Note that in this case the connections of the *p-n* junction diode have been reversed. Also, the milliammeter has been replaced by a microammeter since the reverse current is expected to be small.

Fig. 9.13: **Circuit diagram for the *I-V* characteristics of a *p-n* junction diode in reverse bias.**

Check the circuit connections and follow the steps given below to take observations.

1. Turn the voltage control knob of the power supply to its minimum position and then switch it on. Increase the voltage (from minimum) in steps of 1 V and note corresponding values of current in Observation Table 9.2.

2. <u>**Take care that you do not increase the applied voltage beyond the peak inverse voltage rating of the diode. This is to limit the current in the circuit. Otherwise, the diode can get damaged.**</u>

3. Next decrease the applied voltage in the same steps and note down the corresponding current values. Record these values also in Observation Table 9.2. Are the values of current same in both cases?

4. Calculate the mean value of current for each value of *V* and record it in Observation Table 9.2.

Observation Table 9.2: Current-voltage measurements for a reverse-biased *p-n* junction diode

S.No.	Reverse Voltage (V)	Reverse Current (mA)		Mean Reverse Current (mA)
		Increasing voltage	Decreasing voltage	
1.	0.0			
2.	0.1			
3.	0.2			
4.	0.3			
.	.			
.	.			

Now that you have taken the current-voltage readings in both forward and reverse bias of the diode, you are ready to draw the *I-V* characteristic curve for the diode.

9.4.3 Drawing the *I-V* Characteristics

Draw the characteristic curves for both forward and reverse biased conditions by plotting voltage along the *x*-axis and the current along the *y*-axis on a graph paper using a suitable scale.

You should get a graph like the one shown in Fig. 9.14. You can determine the forward and reverse resistances and the knee voltage from this curve.

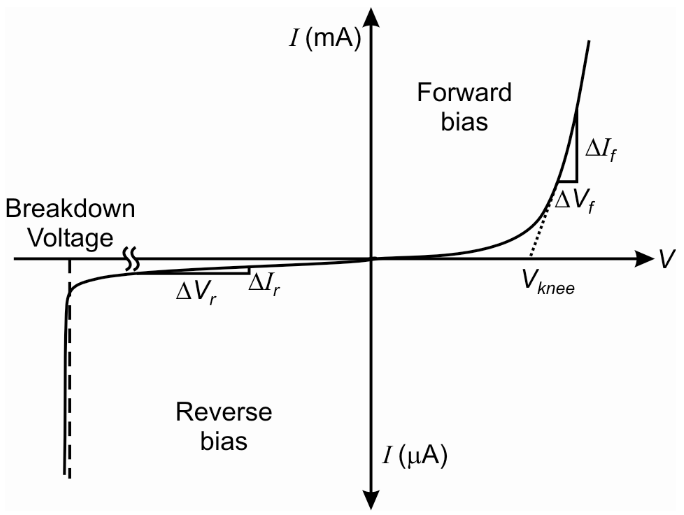

Fig. 9.14: *I-V* **characteristics of a *p-n* junction diode.**

Its slope gives the forward resistance. Extrapolate the linear part of the forward bias characteristic curve to meet the *x*-axis. The intercept on the *x*-axis gives the value of knee voltage.

Now you can do the calculations as follows to determine the forward and reverse resistances of the diode and its knee voltage.

Calculations: From the graph of the *I*-*V* characteristics that you have plotted for the *p*-*n* junction diode, you can calculate the forward resistance R_f and the reverse resistance R_r using the following relations:

$$R_f = \frac{\Delta V_f}{\Delta I_f}$$

and

$$R_r = \frac{\Delta V_r}{\Delta I_r}$$

The intercept of the forward bias characteristic curve on the positive *x*-axis gives the value of the knee voltage. You can read the knee voltage from the graph. Record your results.

Find out the barrier potential of the diode. From Sec. 9.3.1, recall that it depends on the semiconducting material which the diode is made up of.

Result:

Forward resistance = ... Ω

Reverse resistance = ... Ω

Knee voltage = ... V

Write down the sources of error in this experiment in your practical notebook.

We end this experiment with another SAQ based on the results you have obtained.

SAQ 2 – *p-n* **junction diode characteristics**

How will you determine whether a *p*-*n* junction is made of silicon or germanium? What was the material of the *p*-*n* junction diode you characterised in this experiment?